Life and Physical Sciences Research for a New Era of Space Exploration

An Interim Report

Committee for the Decadal Survey on Biological and Physical Sciences in Space
Space Studies Board
Aeronautics and Space Engineering Board
Division on Engineering and Physical Sciences
NATIONAL RESEARCH COUNCIL
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Preface

In response to requests from Congress, NASA asked the National Research Council to undertake a decadal survey of life and physical sciences in microgravity. Developed in consultation with members of the life and physical sciences communities, the guiding principle for the study is to set an agenda for research for the next decade that will allow the use of the space environment to solve complex problems in life and physical sciences so as to deliver both new knowledge and practical benefits for humankind as we become a spacefaring people. The decadal survey will define research areas, recommend a research portfolio and a timeline for conducting that research, identify facility and platform requirements as appropriate, provide rationales for suggested program elements, define dependencies between research objectives, identify terrestrial benefits, and specify whether the research product directly enables exploration or produces fundamental new knowledge. The areas will be categorized as either those that are required to enable exploration missions or those that are enabled or facilitated because of exploration missions. The complete statement of task for the study is given in the appendix to this report.

Among the key tasks in the charge to the Committee for the Decadal Survey on Biological and Physical Sciences in Space are the requests to:

- Define research areas that enable exploration missions or that are enabled by exploration missions;
- For each of the two categories above, define and prioritize an integrated life and physical sciences research portfolio and associated objectives;
- Develop a timeline for the next decade for these research objectives and identify dependencies between the objectives; and
- Identify terrestrial, airborne, and space-based platforms and facilities that could most effectively achieve the objectives.

The committee's final report, expected to be published in early 2011, will address these tasks as well as the others described in the appendix. Like this interim report, the final report will draw on the work of seven study panels organized according to the following themes to address all of the elements of the statement of task: Animal and Human Biology, Applied Physical Sciences, Fundamental Physical Sciences, Human Behavior and Mental Health, Integrative and Translational Research for Human Systems, Plant and Microbial Biology, and Translation to Space Exploration Systems. In addition to the expertise represented by the panels, broad community input has been provided to the study in the form of town hall meetings held in conjunction with professional society meetings, approximately 150 white papers submitted by individuals and teams from the community, and numerous briefings and direct exchanges.

The purpose of this brief interim report, as requested in spring 2010 by the sponsors of the study, is to provide an early indication of near-term issues that may require attention before the committee's recommendations are published in its final report. Although the development of specific recommendations is deferred until the final report, this interim report does attempt to identify near-term programmatic needs and issues that are critical to strengthening the organization and management of the life and physical sciences research enterprise at NASA. It also identifies a number of broad topics that represent near-term opportunities for research on the International Space Station. These areas, along with research more suited to other platforms, including ground-based research, will be examined in greater detail in the final report. The interim report represents a preliminary examination of these issues and topics.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Richard H. Kohrs, NASA (retired),
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A. Thomas Young, Lockheed Martin Corporation (retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the views presented, nor did they see the final draft of the report before its release. The review of this report was overseen by Martha P. Haynes, Cornell University. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Executive Summary

In early 2009 the National Research Council's Committee for the Decadal Survey on Biological and Physical Sciences in Space began work on a study to establish priorities and recommendations for life and physical sciences research in microgravity and partial gravity for the decade 2010-2020. This effort represents the first decadal survey conducted for these fields. The committee is being assisted in this work by seven appointed panels, each focused on a broad area of life and physical sciences research. The study is considering research in two general categories: (1) research *enabled by* unique aspects of the space environment as a tool to advance fundamental and applied scientific knowledge and (2) research that *enables* the advances in basic and applied knowledge needed to expand exploration capabilities. The project's statement of task calls for delivery of two reports—an interim report and a final survey report.

PURPOSE OF THIS INTERIM REPORT

During the period of the decadal survey's development, NASA received guidance in the fiscal year 2011 presidential budget request that directed it to extend the lifetime of the International Space Station (ISS) to 2020. This step considerably altered both the research capacity and the role of the ISS in any future program of life and physical sciences microgravity research. In addition, the budget initiated other potential changes that might affect both the organization and the scale of these programs at NASA. The purpose of this interim report is to provide timely input to the ongoing reorganization of programs related to life and physical sciences microgravity research, as well as to near-term planning or replanning of ISS research. Although the development of specific recommendations is deferred until the final report, this interim report does attempt to identify programmatic needs and issues to guide near-term decisions that the committee has concluded are critical to strengthening the organization and management of life and physical sciences research at NASA. This report also identifies a number of broad topics that represent near-term opportunities for ISS research. Topics discussed briefly in this interim report reflect the committee's preliminary examination of a subset of the issues and topics that will be covered in greater depth in the final decadal survey report.

PROGRAMMATIC ISSUES FOR STRENGTHENING THE RESEARCH ENTERPRISE

As the result of major reorganizations and shifting priorities within the past decade at NASA, there is currently no clear institutional home within the agency for the various scientific endeavors that are focused on understanding how biological and physical systems behave in low-gravity environments. As NASA moves to rebuild or restructure programs focused on these activities, it will have to consider what elements to include in that program.

In its preliminary analysis, the committee has identified a number of critical needs for a successful renewed research endeavor in life and physical sciences. These include:

- Elevating the priority of research in the agenda for space exploration;
- Selecting research likely to provide value to an optimal range of future mission designs;
- Developing a comprehensive database that is accessible to the scientific community;

- Implementing a translational science component to ensure bidirectional interactions between basic science and the development of new mission options; and
- Encouraging, and then accommodating, team science approaches to what are inherently complex multidisciplinary challenges.

In addition, as noted repeatedly by the scientific community that has provided input to this study, reasonable stability and predictability of research funding are critical to ensuring productive and sustained progress toward research goals in any program.

In the context of an institutional home for an integrated research agenda, the committee noted that program leadership and execution are likely to be productive only if aggregated under a single management structure and housed in a NASA directorate or other key organization that understands the value of science and has the vision to see its potential application in future exploration missions. Ultimately, any successful research program would need to be directed by a leader of significant gravitas who is in a position of authority within the agency and has the communication skills to ensure that the entire agency understands and concurs with the key objective to support and conduct high-fidelity, high-quality, high-value research.

INTERNATIONAL SPACE STATION RESEARCH OPPORTUNITIES

The International Space Station provides a unique platform for research, and past studies have noted the critical importance of its research capabilities to support the goal of long-term human exploration in space.[1] Although it is difficult to predict the timing for the transition of important research questions from ground- to space-based investigations, the committee identifies in this interim report a number of broad topics that represent near-term opportunities for ISS research. These topics, which are not prioritized, fall under the following general areas:

- Plant and microbial research to increase fundamental knowledge of the gravitational response and potentially to advance goals for the development of bioregenerative life support;
- Behavioral research to mitigate the detrimental effects of the spaceflight environment on astronauts' functioning and health;
- Human and animal biology research to increase basic understanding of the effects of spaceflight on biological systems and to develop critically needed countermeasures to mitigate the negative biological effects of spaceflight on astronauts' health, safety, and performance;
- Physical sciences research to explore fundamental laws of the universe and basic physical phenomena in the absence of the confounding effects of gravity; and
- Translational and applied research in physical sciences that can provide a foundation of knowledge for the development of systems and technologies enabling human and robotic exploration.

This report contains discussion of various topics within each of these areas. The committee notes, however, that although the ISS is a key component of research infrastructure that will need to be utilized by a biological and physical research sciences program, it is only one component of a healthy program. Other platforms will play an important role and, in particular, research on the ISS will need to be supported by a parallel ground-based program to be scientifically credible.

[1] See, for example, National Research Council, *Review of NASA Plans for the International Space Station,* The National Academies Press, Washington, D.C., 2006.

1
Rationale and Basic Issues

The [Augustine] Committee concludes that the ultimate goal of human exploration is to chart a path for human expansion into the solar system.

—Augustine Committee Final Report (Seeking a Human Spaceflight Program Worthy of a Great Nation), October 2009

The challenges faced by humanity in becoming a spacefaring species have been enormous. The United States has overcome many initial hurdles and delivered the lunar landings, the space shuttle, and, in partnership with other nations, the International Space Station. Looking to the future, significant improvements are needed in spacecraft, life support systems, and space technologies to enhance and enable the human and robotic missions that NASA will conduct under the U.S. space exploration policy. The missions beyond low Earth orbit to and back from planetary bodies and beyond will involve a combination of environmental risk factors such as reduced gravity levels and increased exposure to radiation. Human explorers will require advanced life support systems and be subjected to extended-duration confinement in close quarters. For extended-duration missions conducted at large distances from Earth, and for which resupply will not be an option, technologies that are self-sustaining and/or adaptive will be necessary. These missions present multidisciplinary scientific and engineering challenges and opportunities for enabling research that are both fundamental and applied in nature. Meeting these scientific challenges will require an understanding of biological and physical processes, as well as their intersections, in the presence of partial-gravity and microgravity environments.

Over the past decade NASA and the space enterprise in the United States have deemphasized these scientific challenges in favor of focusing resource allocations toward mission operations. However, to prepare the United States for its future as an enduring and relevant presence in space, science leadership in the life and physical sciences within NASA will need to be reinvigorated. The Committee for the Decadal Survey on Biological and Physical Sciences in Space believes that any compelling future for NASA in space exploration will flow in large part from advances made in a strong life and physical sciences program. The research opportunities and imperatives that will be identified in the final decadal survey can be achieved most rapidly and efficiently by establishing a multidisciplinary and integrated research program within NASA itself. Such a program is needed to span the gaps in knowledge that represent the most significant barriers to extended human spaceflight exploration. A successful program will be dependent on the results of research that is possible only in the unique microgravity environment of space and will embody both life and physical sciences in a manner that facilitates multidisciplinary translational approaches to complex problems.

One of the most important elements of success for a NASA life and physical sciences research program is the stature of research within the Exploration Systems Mission Directorate at NASA. A healthy and sustainable research program of the type that will be outlined in the final report of the decadal survey is needed. Such a program (which is completely consistent with the ultimate mission of NASA as a scientific entity) would provide a foundation for the future of the human exploration program. However, the committee believes that the new research program that the decadal survey will elucidate is unlikely to be successful unless it (1) has the vigorous support of the exploration elements of NASA; (2) comprises co-located components that encourage appropriate interdisciplinary collaboration on efforts that reflect

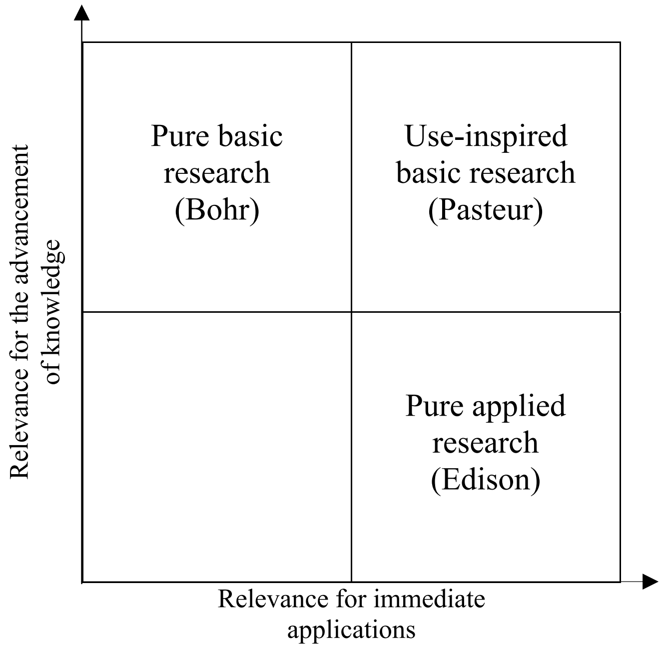

FIGURE 1.1 Stokes begins *Pasteur's Quadrant* with an analysis of the twin goals of developing new understanding and developing results that have an end use in scientific research, and he recasts the widely accepted view of the tension between understanding and use, building a convincing case that, by recognizing the importance of use-inspired basic research, we can frame a new compact between science and government. In *Rising Above the Gathering Storm,* the authoring committee pointed out that some research can simultaneously be inspired by use and also seek fundamental knowledge.

the most important, shared visions and goals for NASA; and (3) has the appropriate processes and mechanisms in place to expedite the translation of basic research findings into practical applications and products, as appropriate. Ultimately, in the committee's view, successful research programs are directed by a leader of significant gravitas who is in a position of authority within the agency and has the communication skills to ensure that the entire agency understands and concurs with the key objective to support and conduct high-fidelity, high-quality, high-value research.

To improve the NASA research enterprise for life and physical sciences, and to facilitate a framework of multidisciplinary and multi-partner collaborations guided by a process of translation from discovery to missions, a sea-change in philosophy and approach will be needed in the exploration program at NASA. This sea-change (described below) can be introduced using the concepts illuminated in the book *Pasteur's Quadrant*[1] by Donald Stokes (and discussed in the 2007 National Academies report *Rising Above the Gathering Storm*[2]) (see Figure 1.1). By segregating basic research from mission-driven research in a linear funding model, and by ignoring Pasteur's Quadrant, the exploration program at NASA was able to justify a reduction in funding of the basic research program with the assumption that the agency could "get back to it" when pressing mission problems were solved and funding levels improved. Overt recognition is needed of Pasteur's Quadrant, and of the intimate, ongoing circular link between basic research and research to meet mission requirements. Critical to the success of such a program is

[1] D.E. Stokes, *Pasteur's Quadrant,* Brookings Institution Press, Washington, D.C., 1997.

[2] National Academy of Sciences, National Academy of Engineering, Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* The National Academies Press, Washington, D.C., 2007.

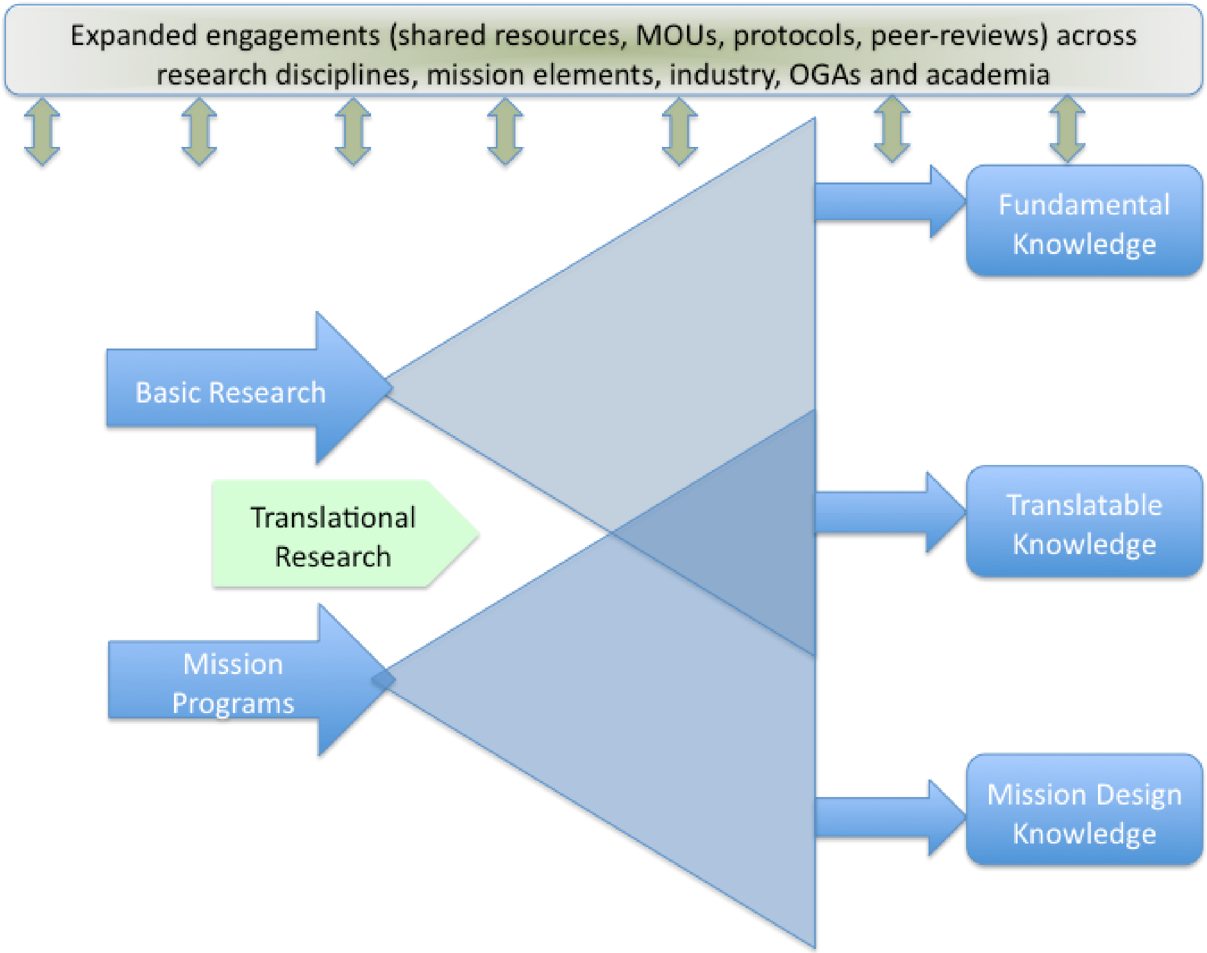

FIGURE 1.2 Translational research as a component of an active research program.

inclusion of a translational element. Translating basic science discoveries into practical applications and solutions to real-world problems is a challenging task.

Translational research (see Figure 1.2) as pioneered by the National Institutes of Health is defined as "the process of applying ideas, insights, and discoveries generated through basic scientific inquiry to the treatment or prevention of human disease."[3] The Department of Energy has hailed translational research as a core focus of its new ARPA-E program[4] (ARPA-E will fund energy technology projects that translate scientific discoveries and cutting-edge inventions into technological innovations, and it will also accelerate technological advances in high-risk areas that industry is not likely to pursue independently). The National Science Foundation has created whole new funding opportunities around translational science (e.g., NSF Translational Research in the Academic Community, NSF-10-044 Program). The form that translational research takes is likely to vary widely according to the needs of the given project. Some examples cited in the NSF announcement include "prototyping, proof of concept tests and/or scale-up or implementation."[5]

There are several reasons for the new emphasis on translational research. One is to fill real and pressing needs for answers to grand challenges in health, energy, climate, and national security. A number

[3] See http://grants1.nih.gov/grants/guide/pa-files/PAR-02-138.html.
[4] See http://apps1.eere.energy.gov/news/news_detail.cfm/news_id=12478.
[5] See http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503524.

of factors have combined to impede the flow of information between basic science and complex applications, perhaps most notably a lack of sufficient resources to support early studies and the challenges involved in sufficient testing at any scale to transition new ideas into practice in high-risk, high-value endeavors. The new focus on translational research aims to remove these obstacles and overtly facilitate and expedite the practical application of scientific discoveries. Another reason for the interest in translational research approaches is an increasing recognition that the pace at which basic scientific discovery has transitioned to societal value has not kept up with the pace of change in society, and particularly with the pace of information flows. Finally, in NASA's exploration missions, there is increasing awareness in the science community that observations from ground-based models do not extrapolate well to space environments, particularly when considering placing humans in these environments for long-duration missions.

In order for a translational research component to become part of an active research program there must be:

1. Mechanisms for horizontal integration,[6] based on multi- and transdisciplinary approaches to complex problems; and
2. Mechanisms for vertical translation,[7] based on meaningful interactions among basic researchers, applied and mission-focused scientists, engineers, administrators, and other professionals.

Human exploration missions beyond the ISS will introduce many challenges related to long-duration isolation and exposure to micro- and partial-gravity, and extreme thermal and radiation, environments. These challenges must be overcome in a manner that optimizes crew safety and the likelihood of achieving scientific mission goals, while containing costs and minimizing schedule uncertainties. Many of these challenges will be solved only by obtaining fundamental new knowledge and then efficiently translating that knowledge to new options for exploration missions.

Current deficits in scientific knowledge and the erosion of the relative stature of the United States in space exploration activities have, in part, been the result of inconsistent funding policies over the past several years. In addition to the level of funding per se, consistency of funding is necessary over time frames necessary to build a scientific enterprise, develop a pipeline of researchers, and allow their studies to bear fruit. Unfortunately, in 2004-2005, NASA's life and physical sciences community suffered an abrupt and substantial funding decrement. As a result, many of the affected scientists are wary of returning to NASA-related work—a problem noted in the white papers and town hall meetings associated with the decadal survey. The institution of a research program with consistent goals, stable funding, and a real desire to seek new knowledge and solve important problems will help initiate the process of rebuilding NASA's (and the United States') capabilities in this vital area of scientific endeavor.

In terms of research infrastructure for a life and physical sciences program, the ISS, while unique, is not the sole operational site. Many platforms, including terrestrial, will continue to be important for executing a coherent, integrated, multidisciplinary program—and the utility of these research platforms will be explicated in the final report of the decadal survey. However, the continuing great importance of the ISS warrants more immediate consideration and comment. Currently, the ISS is the only space platform available for near-term studies that require long-duration exposure to microgravity. It is also the only platform available today where experiments that require many repetitions for statistical validity can be conducted in a common microgravity environment. For the ISS to advance the science under consideration, the most crucial requirement is ensuring the will and commitment to exploration science. As discussed in Chapter 2 of this interim report, there are substantial problems with translational research efforts in space exploration. A critical advantage of the ISS is that it provides a platform for research programs that can, in fact, be translational. The committee believes that, to optimize the use of this

[6] Integration of disciplines, scientific subdisciplines, and systems disciplines.
[7] Integration of information, people, requirements, and discoveries across all elements of the NASA Exploration tasks, from basic research through mission design, to use in mission applications.

research platform, and as part of setting up a revitalized research program in the life and physical sciences, initial efforts to develop a research program for the ISS will have to include an advisory process, utilizing at least some independent members, that provides oversight for the prioritization of ISS (and other) research as multidisciplinary research priorities, operational requirements, cost constraints, and policy priorities are being developed by the new administration.

In this context, this interim report (1) discusses programmatic issues that are viewed as fundamental for a life and physical sciences research program and (2) presents suggestions for ISS research that can help steer the active discussions regarding additional lifespan for the ISS yet at the same time does not abrogate the prioritization process that is underway across the whole portfolio as part of the committee's final survey report, which will give fuller consideration to all platforms and modalities of research.

2
Programmatic Issues

NASA faces numerous challenges in carrying out the aspirations of the United States to advance its space exploration mission. Over its 50-year history, NASA progress in space exploration has depended on the ability to address a wide range of biomedical, engineering, physical science, and other challenges. The partnership of NASA with the research community reflects the original mandate from Congress in 1958 to promote science and technology, which requires an active and vibrant research program. This level of programmatic vision and dedication to scientific excellence is no less important today as NASA prepares to tackle the considerable hurdles that must be surmounted before the goal of long-duration human exploration missions in space can be realized. As has always been the case, achievement of these goals will depend on a steady stream of results from high-quality research. However, more than ever before, it will be necessary for NASA to embrace life and physical sciences research as part of its core exploration mission, and to develop an energized community of life and physical scientists and engineers with a strong focus on both exploration-enabling research and scientific discovery (i.e., fundamental research enabled by space exploration). Importantly, life and physical sciences research needs to be viewed as essential to the NASA exploration mission and to be given correspondingly appropriate recognition in the organization.

The scientific community engaged in space exploration research has dwindled as a result of marked reductions in budget funding levels, from approximately $500 million shared equally between life and physical sciences in 2002 to the current level of about $180 million, and the concomitant reduction in the ISS research portfolio, from 966 investigations in 2002 to 285 in 2008.[1] Considerable effort will be required to overcome current obstacles and restore the life and physical sciences research program to a committed, comprehensive, and highly visible organizational resource that effectively promotes research to meet the national space exploration agenda. This goal can be best achieved with a portfolio that supports both intra- and extramural programs (i.e., similar to the NIH support of intra- and extramural research), including a program of ground-based research. To advance an appropriate program of basic and translational research, the most scientifically meritorious and programmatically relevant research should be identified and promoted. It is a generally accepted principle that a rigorous and transparent peer review process is an important means of identifying meritorious scientific research. In addition, agency-specific programmatic needs will have to be taken into account in maintaining a high-quality research portfolio. A successful and transparent review system would be based on scientific merit, as judged by peer review, and programmatic relevance, as determined by internal review, and would result in the assembly of a research portfolio that continuously generates new ideas and translates them to new missions.

The development of integrated multidisciplinary team science, both within and across the life and physical science communities, will likely become important to the delivery of science to close knowledge gaps, reduce costs and risks, and enable new missions. Overall, an organizational focus on the research mission, an appropriate research solicitation and review process, a strong outreach to the larger research community, and a strategy to develop a new generation of scientists and engineers that will enhance the future workforce represent important mechanisms to meet NASA goals. These issues are discussed in more detail in the following sections.

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[1] David L. Tomko, "History of Life and Physical Sciences Research Programs at NASA," presentation to the Committee for the Decadal Survey on Biological and Physical Sciences in Space, Washington, D.C., May 6, 2008.

PROGRAMMATIC ISSUES FOR STRENGTHENING THE RESEARCH ENTERPRISE

Elevating the Priority of Life and Physical Sciences Research in Space Exploration

When NASA was established by Congress in 1958, its critical roles as both the driver and the beneficiary of future U.S. scientific and technological advances were widely recognized. It is noteworthy that the enabling of scientific inquiry by space exploration was a critical issue during the inception of the agency and, half a century later, the promotion of scientific and technological advancement endures as a key imperative for NASA. Scientific advances go to the core of the NASA mission because they enable future space exploration.

As the nation and NASA prepare for the next decade of space exploration, numerous challenges must be met to ensure successful outcomes. Among these are the developments needed to buy down risks and costs, an effort that will depend on a deeper understanding of the performance of people, materials, microbes and plant life, and physical systems in the environments of space. To meet these challenges, which span the life and physical sciences, it is essential to develop a long-term, strategic research plan firmly anchored in a broad research community. For such a plan to become a reality, research must be central to NASA's exploration mission and be embraced throughout the agency as an essential tool to achieve future space exploration goals. Feedback received by the committee from numerous interviews, town hall meetings, and white paper submissions associated with this decadal survey indicated that a very large proportion of the research community does not see such an environment currently within the exploration programs at NASA, at least with regard to the life and physical sciences.

NASA has faced a number of challenges in fulfilling the original objectives identified by Congress. It has been a challenge from the outset to organize and manage the life and physical sciences research program within the overall NASA administrative infrastructure. Some of the organizational challenges have included the ability to select and prioritize the most meritorious research projects, the provision of adequate and sustained support for such research projects, the ability to draw on a community of scientists with the necessary skills and experience to conduct these studies, and the ability and will to create a new generation of scientists and engineers focused on research questions relevant for space exploration missions. To meet these challenges, it is of paramount importance that the life and physical sciences research portfolio supported by NASA, both extramurally and intramurally, receive appropriate attention and that the organizational structure be optimally designed to meet NASA's needs. The utility of a coherent research plan that provides appropriate resources and is consistently applied to enable exploration cannot be overemphasized. This is especially the case given the frequent and lengthy postponements that NASA's exploration-related goals have experienced over the past several decades.

The NASA exploration research enterprise will be improved only if it is emphasized throughout the organizational structure of NASA. Because the agency prioritized goals for building flight infrastructure for the Constellation Project at the expense of maintaining a vigorous life and physical sciences research program, this important research program has been relegated to a very-low-priority status with many areas virtually eliminated. Since retirement of the Spacelab (in 1997) and the completion of the International Neurolab project (mission conducted in 1998)—in which many sophisticated experiments took place in the context of dedicated research missions implemented by a highly trained and intellectually engaged crew—the priority for research has been reduced to levels that compromise not only the research endeavor but also the likelihood of success in future exploration missions. The view of research as optional, rather than essential, is reflected in the attitudes of flight and ground personnel toward crew participation in research projects and appears to be driven by NASA's overall expectations and its reward system for flight missions. Currently, astronauts can opt out of their participation in approved and manifested research projects, in terms of both serving as a subject in and acting as a surrogate investigator for a research project. Mission managers, who often have no research background and are not given incentives to place a priority on research, have the authority to control crew availability and make decisions about crew scheduling that can compromise research studies and outcomes, even when acceptable alternatives to these competing activities are available.

To address these systemic problems and improve the results of NASA's life and physical sciences research program over the next decade, the following issues are viewed by the committee as important:

- *Recognition that a change of attitude and commitment toward the need for life and physical sciences research is essential*. To ensure that life and physical sciences research is recognized as central to NASA's space exploration mission, research itself needs to be viewed as a priority. However, an emphasis on research is often not evident in day-to-day decisions. It is essential that every employee, from management through crew, subscribe to the view that a key objective of the organization is to support and conduct life and physical sciences research as an essential translational step in the execution of space exploration missions.
- *Acknowledgment of life and physical sciences research as an integral component of spaceflight operations.* For research to become a central component of exploration programs, it is necessary to develop a culture in which participation in research, both as a subject of investigation and as a surrogate investigator, is viewed as a fundamental element of the astronaut mission. Many crew members already display this attitude, and they frequently go to extraordinary lengths to participate in research studies in partnership with the extramural research community. However, the level of autonomy astronauts have in choosing whether or not to participate in research is surprising, given the need to capitalize on the very scarce opportunities for human research in space. In addition, many types of experiments require individuals with specialized scientific or technical expertise to make knowledgeable observations, measurements, and judgments. It is important to optimize very scarce opportunities to gain a better understanding of the effects of the space environment on human health, safety, and performance because such information will define the future limits of space exploration. One possible solution is to include scientific and technical expertise, and willingness to participate in research, as part of the criteria for crew selection in the planning of specific mission assignments, and perhaps even as part of the astronaut selection process. It is also important that the high priority of research be reinforced during the training provided to ground support personnel (e.g., flight directors, mission controllers, training managers, and instructors). This approach would require careful thought as to its precise implementation because it must also take into account concerns about such issues as coercion and privacy rights. However, it seems reasonable and ethical that, if research participation is defined as part of a mission's task, then the consequence of choosing not to participate would be understood as leading to assignment of a different type of job. This approach would remain aligned with the Federal Policy for the Protection of Human Subjects.[2] Because the NASA exploration mission is of national importance, research opportunities to advance this agenda become part of strategic decisions. This philosophy is consistent with that embodied in the National Aeronautics and Space Act of 1958[3] and in the reports *Safe Passage*[4] and *A Strategy for Research in Space Biology and Medicine in the New Century.*[5]

Establishing a Stable and Sufficient Funding Base

A renewed funding base for fundamental and applied life and physical sciences research is essential for attracting the scientific community that is needed to meet prioritized research objectives. Scientists must have a reasonable level of confidence in the sustainability of research funding if they are to be expected to focus their laboratories, staff, and students on research relevant to space exploration. Given the time frame required for completion of the types and scales of experiments necessary for space exploration, grant funding mechanisms would have to cover multiple years, with contingencies for delays

[2] See http://www.hhs.gov/ohrp/policy/common.html.
[3] National Aeronautics and Space Act of 1958.
[4] Institute of Medicine, *Safe Passage: Astronaut Care for Exploration Missions,* National Academy Press, Washington, D.C., 2001.
[5] National Research Council, *A Strategy for Research in Space Biology and Medicine in the New Century,* National Academy Press, Washington, D.C., 1998.

in flight experiments. A stable research funding level is essential for reinvigorating the scientific community that will not only carry out the research to enable future space exploration, but also advance scientific discoveries that are enabled by space exploration and educate future generations of space scientists.

As discussed above, a healthy space exploration research program would support both intramural and extramural research, including a highly developed ground-based research program to inform and complement space-based research. An intramural program is essential to ensure that there are timely and ongoing research efforts focused on barriers that currently limit space exploration. An extramural program increases the intellectual wealth and breadth of innovative crosscutting ideas to stimulate advances in both space exploration capabilities and fundamental scientific discoveries. A robust and sustained extramural research program also ensures that there will be a stable community of scientists prepared to lead future space exploration research.

Life and physical sciences research for space exploration can potentially be supported by many federal agencies, but, to date, efforts to align and coordinate research programs between such agencies have been relatively limited. This may be due, in part, to the different missions of the respective agencies. However, there is a growing need to achieve synergies in multiagency efforts (as discussed below). An increased coordination among agencies would be expected to harness and leverage existing resources. Possible mechanisms for encouraging interagency collaborations include:

- Dedicated interagency funds for technology development or research in the space environment that serves a dual use, both for NASA and for another agency,
- Interagency strategic resource planning,
- Use of a similar review process,
- Continued use of interagency workshops and symposia,
- Interagency dual-use technology pilot grant programs, and
- Interagency, interdisciplinary training programs involving mentors.

The success of interagency initiatives will depend on support for such initiatives across the agencies, creation of a spirit of collaboration, and development of new partnerships leading to novel research teams. A comprehensive interagency team effort will serve as a creative scientific resource for implementation of a comprehensive space exploration research program.

Improving the Process for Solicitation and Review of High-Quality Research

Scientists who plan to compete for major research grants typically conduct preliminary studies years in advance of submitting a grant application. Thus, familiarity with the research solicitation process is critical for researchers to sustain activities in their laboratories that enable them to prepare proposals for high-quality research. A regular frequency of solicitations, ideally with multiple solicitations per year, would serve to maintain a community of investigators focused on life and physical science research areas relevant to the agency, thereby creating a research network. This approach is used successfully by major granting agencies, including the NIH and NSF. It is an important goal for any funding agency to ensure that supported research projects are aligned with agency needs. To meet NASA's future space exploration goals, complex scientific and engineering problems need to be tackled. Many of these problems will require team-based solutions bridging multiple scientific domains. Accordingly, research solicitations will need to target both individual principal-investigator-driven and team-driven research. Further, solicitations would need to include both broad research announcements in order to encourage highly innovative research grant applications, and targeted research announcements to ensure that high-priority mission-oriented goals are met. This multifaceted solicitation approach would be expected to attract cutting-edge life and physical sciences research that both enables and is enabled by space exploration.

Beyond the mission of any single funding agency, a coordinated interagency collaboration is likely to significantly enhance the opportunities for progress in research areas critical to space exploration. However, success from such an interaction will depend on the degree to which the collaboration is embraced by all stakeholders and seen as important to the mission of the specific agency. It is important to direct special attention to flight hardware development for a particular experiment, where such costs may not be embraced by the funding agencies. It is promising that there are model collaborations from existing interdisciplinary programs in place, such as the NIH Clinical and Translational Science Award (CTSA) program, Ecology of Infectious Diseases (NSF and NIH), National Plant Genome Initiative (NSF, NIH, USDA, DOE, USAID, OSTP, and OMB), and the UK Engineering and Physical Sciences Research Program. An advantage of interdisciplinary programs is a shared contribution of several agencies to the amount of funding needed for ambitious and expensive projects that likely will be necessary to enable space missions. It would be valuable to strengthen and sustain the historical collaborations of NASA with agencies such as the NIH, as well as to expand them to other agencies such as the DOE and DOD. These collaborations can build on such efforts as the *Memorandum of Understanding between the National Institutes of Health and the National Aeronautics and Space Administration for Cooperation in Space-Related Health Research*, which went into effect in September 2007.[6] This memorandum of understanding established a framework of cooperation between the NIH and NASA to encourage (1) communication and interaction between the NIH and NASA research communities to facilitate space-related research and to integrate results from that research into an improved understanding of human physiology and human health; (2) the exchange of ideas, information, and data arising from their respective research efforts; (3) the development of biomedical research approaches and clinical technologies for use on Earth and in space; and (4) research in Earth- and space-based facilities that could improve human health on Earth and in space.

The research community that deals with life and physical sciences in space has remained quite robust internationally, even as NASA has reduced its support in this area. Investigations in Japan, Europe, and Russia have continued, with new results being published continuously. To regain a place as a member of the global scientific team in life and physical sciences in space, there is a need for the United States to increase international scientific activities, through interactions with such organizations as, but not limited to, the International Space Station Life Sciences Working Group (ISSLSWG). Such cooperation worked well in the decades before 2000 and will undoubtedly reduce costs to NASA. New partnerships, such as with India, Australia, and China, are possible. Strong interactions with groups such as ISSLSWG and the offering of joint research announcements with international partner agencies will aid discovery and internationalize space life sciences, offering opportunities for collaboration in ground-based studies prior to flight experiments.

The United States has enjoyed a leadership position in space exploration due to its long and successful history of space missions. However, during the coming decade, it is likely that significant efforts in this area will be initiated by other nations. Because there are unresolved problems in ensuring safe and successful long-duration missions that affect all nations attempting human spaceflight, a convergence of efforts would likely be of universal benefit. Similar steps as discussed above regarding interagency collaboration within the United States seem logical to explore in support of international scientific projects designed to resolve issues relevant to technological challenges and astronaut health and welfare.

The process of peer review is firmly established as a mechanism for identifying the most meritorious research in any scientific area. The concept is universally embraced by the global research community and viewed as a guarantor for a transparent, fair, and equitable process that results in significant scientific progress. For both life science and physical scientists, the peer review process utilized by many federal agencies is well known, and the research community as a whole has significant experience in navigating such processes. In addition, many researchers serve on peer review panels in a volunteer capacity and see these efforts as a vitally important societal responsibility and a demonstration

[6] See http://nihrecord.od.nih.gov/newsletters/2007/10_19_2007/story1.htm.

of the inclusion of the broad scientific community in meeting the goals of the sponsoring agency. In this context, the legitimacy of the peer review process is highly dependent on the adoption of panel or study-section recommendations by the respective funding agencies, and lack of adherence to recommendations raises the risk of alienating the research community. It is the committee's belief that NASA has a well-designed peer review system for the evaluation of extramural research applications. However, it is also the strong opinion of the committee that the standards for the "non-advocate review" of intramural research could be elevated by ensuring that the review process, including the actions taken by NASA as a result of review recommendations, is more transparent with a clear rationale for prioritizing both intra- and extramural investigations. Past NRC reports have noted that spaceflight opportunities should unconditionally give maximal access to peer-reviewed experiments that have a strong basis in ground tests and spaceflight performance verifications.[7] Given the severe limitations of actual spaceflight access, it is important that spaceflights do not carry science that has not been deemed of high merit by peer review and prioritized by NASA or formal NASA science partnerships. As part of this effort, it is also important that NASA coordinate agency assets, commercial payload developers, and flight systems developers in a manner that serves the best science and reduces the end-to-end time for flight experiments.

Rejuvenating a Strong Pipeline of Intellectual Capital Through Training and Mentoring Programs

Realizing the growing challenge of the need to rapidly translate basic findings to applications, the biomedical research enterprise in the United States has reorganized to expand the emphasis on education and training programs for target audiences, ranging from practitioners to researchers to students, as one way to expedite the translation of discoveries to practice. One successful vehicle for these efforts, for example, is the recently launched, NIH-funded Clinical and Translational Science Award (CTSA). An ancillary goal of these programs is to increase the number and quality of collaborations among practitioners, scientists, patients, and administrators.

The NIH model of expanded research education offers clues as to how NASA could design unique educational programs that improve translation of the research in the life and physical sciences by including some or all of the following elements:

- *A curriculum-based program for flight surgeons and physician-astronauts to expand their research knowledge and skill set.* Such programs are comparable to the NIH team-based K30 awards (clinical research curriculum awards).
- *Mentored research training of junior faculty in biomedical sciences, similar to the NIH K (career development) awards*. An essential element of these programs is their demand that a majority of a trainee's time be protected for instruction and research. When such expectations are not feasible or practical, CTSAs often provide continuing and professional education in specific areas of research.
- *Career enhancement awards for junior faculty in nonmedical life sciences, physical sciences, and engineering.* In the physical sciences and engineering, and in many nonmedically related disciplines in the life sciences, junior faculty are expected to develop independent research portfolios upon their academic appointment. Thus, to attract new talent, it is essential to create funding mechanisms targeted specifically to junior faculty. These typically provide significant multiyear support and also confer prestige. Examples from which NASA could draw to develop such an award program include the NSF CAREER Award, the Office of Naval Research Young Investigator Program, the Air Force Office of Scientific Research Young Investigator Program, the Army Research Office Young Investigator Program, the DARPA Young Faculty Award, and the DOE Early Career Research Program.

[7] See, for example, National Research Council, *A Strategy for Research in Space Biology and Medicine in the New Century,* National Academy Press, Washington, D.C., 1998.

Similar programs, if tailored to the concerns of extended-duration spaceflight, could also provide meaningful opportunities for management personnel, engineers, physicians, and astronauts to expand their understanding of the research payloads for which they are responsible. Moreover, such programs could include combinations of virtual and traditional modes of instruction.

Further, a strong pipeline of intellectual capital can be developed by modeling a training and mentoring program after other successful programs in the life and physical sciences. A critical number of investigators is required to sustain a healthy and productive scientific community. Building a program in the life and physical sciences would benefit from ensuring that an adequate number of investigators, including flight and ground-based investigators, are participating in research that will enable future space exploration.

Linking Science to Mission Capabilities Through Multidisciplinary Translational Programs

Complex systems problems of the type that crewed missions will increasingly encounter will need to be solved with integrated teams that are likely to include scientists from a number of disciplines as well as engineers, mission analysts, and technology developers. The interplay between and among the life and physical sciences, along with a strong focus on cost-effectiveness, will require multidisciplinary approaches. Multidisciplinary translational programs can better link the science to the gaps in mission capabilities through comprehensive data collection and data-sharing mechanisms that facilitate access by the scientific community.

Centralized Information Networks

Centralized information networks based on NASA-sponsored research that are accessible to intramural and extramural investigators would be a very valuable research tool. Modern analytical techniques offer a tremendous opportunity to understand the effects of spaceflight on life and physical science systems. Such techniques generate vast amounts of data that can be mined and analyzed for information by multiple researchers. An example is the National Human Genome Research Institute's Encyclopedia of DNA Elements (ENCODE) project.[8] The creation of a formalized program to promote the sharing and analysis of such data would greatly enhance the science derived from flight opportunities. Elements of such a program would include guidelines on data sharing and community access, with a focus on rapid release of data sets while respecting the rights of the principal investigators. A program of analysis grants dedicated to the spaceflight-derived data sets, which should include operational medical data, would provide value-added interpretation while ensuring that all data are maximally mined for information. Larger-scale multiple investigator experiments with related science objectives, methods, and common data products would result in the production of large data sets and would emphasize analysis over implementation. This type of data set, which is similar to those used by the space and Earth sciences, would likely be a tremendous resource for student research.

Research Team Approach

As noted in Chapter 1 of this interim report, a life and physical sciences research program to address the complex problems posed by space exploration will need to include both horizontal integration across multiple disciplines and vertical translation of fundamental discoveries to practical application. As an example, the loss of bone and muscle will remain a barrier to prolonged spaceflight until effective countermeasures are developed. Although exposure to microgravity per se triggers bone and muscle loss because of the reduction in mechanical loading forces, losses are likely exacerbated by additional factors in the space environment (e.g., altered nutrition, hormonal disruptions, psychological stress). Thus, the

[8] See http://www.genome.gov/ENCODE/.

development of effective countermeasure strategies will require input from experts across multiple disciplines (e.g., basic bone and muscle biologists, cardiovascular physiologists, endocrinologists, exercise physiologists, nutritionists, biomechanists, behavioralists). Further, physical scientists and engineers will need to work side by side with life scientists to ensure that countermeasures can be implemented in the space environment.

Beyond meeting the need to provide scientific underpinnings to fulfill future space exploration goals, the space research community represents an ideal foundation around which life and physical scientists and engineers can coalesce to address common goals. Because scientific advances can occur as a result of serendipity, it is important to have life scientists, physical scientists, and engineers working side by side to take full advantage of both planned and serendipitous discoveries. Examples of the benefits of multidisciplinary interactions include the development of protective gear, and issues related to temperature control during extravehicular activity have engaged both the life and the physical sciences communities. However, at this time, a broad-based, multidisciplinary, integrative approach to conducting space exploration research has not been formally implemented. Clearly, given the scarce opportunities to carry out scientific studies under extraterrestrial conditions, careful planning is needed to optimize efficiencies. Although a considerable amount of planning has occurred to ensure efficient and optimal use of such research opportunities within the respective life or physical sciences communities, a concurrent and simultaneous implementation of life and physical sciences experiments would provide opportunities to obtain further synergies from research: a long-term strategic plan to maximize team research opportunities and initiatives could be expected to lead to more efficient solutions to the complex problems associated with space exploration. Implementing such initiatives would require forming integrative teams with representation from across the life and physical sciences, as well as from across funding agencies, to assist in this crucial planning process.

Improved Access to Samples and Data from Astronauts

The medical and scientific communities interested in human health, safety, and performance during long-duration spaceflight have been consistent in their requests for greater access to biological samples and other data collected from astronauts before, during, and after space missions. The rights of astronauts to privacy have, at times, appeared to conflict with the need for access to valuable data to benefit future space travelers. The 2001 Institute of Medicine report *Safe Passage: Astronaut Care for Exploration Missions*[9] included suggestions for resolving this conflict. Among the recommendations were that NASA should (1) establish a comprehensive health information system for astronauts, for the purpose of collecting and analyzing data, and (2) develop a strategic research plan designed to increase the knowledge base about the risks to astronaut health. Some of these goals have been met, but much remains to be done to provide more widespread scientific access to such data.

There are potentially three different types of research that are important for advancing knowledge of the biological effects of the space environment, each with unique strategies for collecting biomedical data. The first is hypothesis-driven experiments designed for space which generate data to address specific biological questions. The second type of research capitalizes on routinely captured operational data that could be used to address biomedical research questions. For example, NASA already has extensive operational data (e.g., to enable the precision of navigation maneuvers performed by crew) that could be linked to data on crew characteristics and made available for data mining. Such a database would enable scientists to address such questions as whether astronauts who perform with more or less precision in space are characterized by potential mediators of performance (e.g., sleep disruption, motion sickness). The third type of research is on the persistent effects of spaceflight on health. This research requires the creation of a long-term astronaut health information registry to enable learning what, if any, health problems are encountered by flight crews long after their mission. For example, there is relatively little

[9] Institute of Medicine, *Safe Passage: Astronaut Care for Exploration Missions,* National Academy Press, Washington, D.C., 2001.

knowledge of post-mission long-term changes in the bone health of astronauts who have flown on long-duration space missions. Current policies on the availability of and access to such follow-up data are perceived as limiting progress toward the development of effective countermeasures. A potential strategy that would benefit all three of these research approaches would be the creation of a robust astronaut health study database. The database could be populated retrospectively with currently archived data from the many space research studies that have been conducted, archived data from flight medicine, and available long-term follow-up health data such as the data obtained in the Longitudinal Study of Astronaut Health (LSAH),[10] with plans to expand the database prospectively. Such a database could be generated through a formal research announcement to attract independent investigators who have established similar population databases (e.g., the Nurses' Health Study database). Coupling the database with a genetic bank and repository of astronaut samples would ensure the availability of the maximal amount of data to address future investigations. Because of the limited number of humans who undergo exposure to the space environment, maintaining an extensive and well-organized database and managing it as a resource to be shared with the scientific community have long been viewed as essential steps for scientific discovery.

Ground-based Research

Space research programs are unlikely to advance rapidly unless supported by a highly developed ground-based research program. Ground-based research is an important way to refine technologies for conducting life and physical sciences experiments to a point that precious time in low gravity can be optimized for obtaining important research results. Ground research also provides key information to inform the design and complement the results of space research, thereby maximizing the scientific yield. Experiments conducted in space are complex and expensive. To optimize space-based research opportunities and results, it is important that an enhanced commitment is made to ensure ground-based analogs of spaceflight and complementary ground-based studies for the purposes of life and physical sciences research. The return to society from most space experiments in the fundamental physical sciences depends critically on advancing the state of the art in measurement science, and such advances have to be made and confirmed within a ground-based program, and often as selection criterion for major flight commitments.

An example of an important ground-based analog is head-down-tilt bed rest to simulate the effects of microgravity. This intervention paradigm has been used to evaluate the efficacy of countermeasures aimed at preserving physiologic function during spaceflight.[11] Interventions that have been found to be effective under these controlled conditions of reduced loading (i.e., bed rest) are now being evaluated on the ISS to determine their effectiveness in an environment that includes not only reduced loading (i.e., microgravity) but also multiple other stressors (e.g., psychological, behavioral, nutritional).

Translational Research and Team Science

To meet the demands for new scientific knowledge to guide future space missions, there is a strong need to improve the research productivity pipeline. This might best be addressed by a systematic analysis of where inefficiencies might be occurring in the translational process. In the physical sciences, the gap between the results of basic research studies and successful commercial or government

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[10] The LSAH was reviewed in a 2004 IOM study (Institute of Medicine, *Review of NASA's Longitudinal Study of Astronaut Health,* The National Academies Press, Washington, D.C., 2004).

[11] T.A. Trappe, N.A. Burd, E.S. Louis, G.A. Lee, and S.W Trappe, Influence of concurrent exercise or nutrition countermeasures on thigh and calf muscle size and function during 60 days of bed rest in women, *Acta Physiologica* 191:147-159, 2007.

applications has been referred to for many years as "the valley of death."[12] Clinical and translational scientists in recent years have also begun to define particularly problematic gaps that commonly prove to be the "valley of death" for new drugs, devices, or interventions.

Overcoming or at least minimizing these gaps has been a hallmark of the CTSA program launched by NIH. The kinds of interventions currently being undertaken to improve the process of clinical and translational research in the CTSAs should be generalizable to some aspects of NASA's research enterprise.

One important aspect of the above-mentioned CTSA process is the deployment of informatics capabilities addressing all aspects of the research process so that captured information about all transactions, whether research, contractual, bureaucratic, laboratory, facility, or other types, is monitored to examine inefficiencies that may be delaying, or in some cases sidelining, a rapid and orderly discovery process. As discussed above, this process also provides important tools for increasing communications among scientists and, in the space research area, between NASA and the extramural community of investigators. Hallmarks of this approach include (1) focusing on investigator needs, (2) collecting and analyzing metrics to assist in the evaluation of the success of projects, (3) providing for auditing to ensure that evaluation metrics are available to support program review and future prioritization, (4) leveraging existing resources whenever possible to avoid duplication of effort, and (5) building a well-connected community of investigators.

Developing Commercial Sector Interactions to Advance Science, Technology, and Economic Growth

It is important to ensure that NASA's interactions with the commercial sector are as conducive as possible to the advancement of science, technology, and economic growth. As an example, contract specifications for commercial flight providers may hinder research unless they are formulated with specific requirements to accommodate science needs. Because up-mass and down-mass to the ISS may be delivered by commercial contractors in the future, it is important that the contract specifications for vehicles include adequate capacity for transporting biological and/or inorganic samples. Conditioned down-mass is of particular importance because there are limited facilities on the ISS for storage of samples. Unless suitable down-mass transportation is made available, only the results of the relatively simple analyses that can be conducted on the ISS will be available.

Broad, multidisciplinary teams will be necessary to coordinate and integrate activities across the commercial sector, the space medicine community, and the space operations community. Issues related to the control of intellectual property, technology transfer, conflicts of interest, and data integrity will also have to be addressed.

Commercial suborbital spaceflight is on the horizon and has the potential to provide a platform for the reduced-gravity study of rapidly occurring processes such as combustion phenomena. Several companies are now developing the hardware and procedures for suborbital flights.[13] The flights will be available to the public, initially at high cost but becoming more affordable as operations continue. While flight trajectories and, therefore, dynamics differ among the companies and remain to some extent proprietary, it is reasonable to expect flights to reach peak altitudes in the range of 100 km with flight times of about 15 minutes. Hyper-gravity launch and landing phases will surround a free-fall or near-weightless (milli-*g*) phase of 4 to 5 minutes duration. One aspect that needs to be addressed is how to make flight opportunities available to the research community. A typical NIH or NSF grant, for example, will not support more than one or two such flights, which obviates much of their appeal. One approach is for funding agencies (NASA, NIH, NSF) to pool resources and purchase a set of flights to be dedicated to life and physical sciences, or to research in general.

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[12] National Research Council, *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems,* The National Academies Press, Washington, D.C., 2004.

[13] K. Sanderson, Science lines up for seat to space, *Nature* 463:716-717, 2010.

Vehicles under development by commercial suborbital companies, such as Virgin Galactic, Armadillo Aerospace, Blue Origin, Masten Space Systems, and XCOR Aerospace, will likely provide scientists, university researchers, and students with a new way to access the space environment.[14] The scientific community has reacted enthusiastically to the promise of these vehicles, with more than 200 scientists from around the country participating in a series of workshops with suborbital vehicle developers, a distinguished group of scientists coming together to form the Suborbital Applications Researchers Group, and a conference on next-generation suborbital research. NASA also recognized the potential of commercial suborbital spacecraft and formed the NASA Commercial Re-usable Suborbital Research (CRuSR) Program at NASA Ames Research Center.[15] It is important that these types of educational networking opportunities be fostered to help catalyze research interactions among commercial developers, the scientific community, and NASA.

ADMINISTRATIVE OVERSIGHT OF LIFE AND PHYSICAL SCIENCES RESEARCH

Currently, life and physical science endeavors focused on understanding phenomena in low-gravity environments have no clear institutional home at NASA. As determined by the decadal survey committee from its examination of the highly varied history of these programs, and as commented on in the Augustine Committee Final Report,[16] administratively embedding crucial forward-looking elements such as this in larger or operationally focused organizations virtually guarantees that its resources will be swallowed up by other needs.

The discussion in this chapter has focused on the essential needs for a successful renewed research endeavor in life and physical sciences—the development of a credible agenda, the selection of the research most likely to provide value to an optimum range of future missions designs, the crucial inclusion of a translational science component to continuously build bridges between basic science and the development of new mission options, and the necessity of encouraging and then accommodating team science approaches to what are inherently fully multidisciplinary challenges.

This chapter has also addressed the importance of funding stability. In the context of a programmatic home for an integrated research agenda, it notes that program leadership and execution are likely to be productive only if aggregated under a single management structure and housed in a NASA directorate or key organization that understands both the value of science and its potential application in future exploration missions.

All of these factors emphasize the need for the following elements:

- Leadership with both true scientific gravitas and a sufficiently high level in the overall organizational structure at NASA to have a “voice at the table” when the agency engages in difficult discussions about prioritizing resources and engaging in new activities,
- Unique authority over a dedicated and enduring funding stream, and
- Organizational positioning that allows the conduct of a unique basic research program as well as interactions and influence within the mission-planning elements that develop new exploration options.

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[14] Alan Stern, Southwest Research Institute, “Research and Education and Next-Gen Suborbital Flight,” presentation to the Committee for the Decadal Survey on Biological and Physical Sciences in Space, October 2009.

[15] See http://suborbitalex.arc.nasa.gov/ for more details on the NASA CRuSR Program.

[16] Review of U.S. Human Spaceflight Plans Committee, *Seeking a Human Spaceflight Program Worthy of a Great Nation,* Final Report, 2009, available at http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf, p. 113.

3
Research on the International Space Station

If the life of the ISS is extended, a more robust program of science, human research and technology development would significantly increase the return on investment from the Station and better prepare for human exploration beyond low-Earth orbit.

—Augustine Committee Final Report (Seeking a Human Spaceflight Program Worthy of a Great Nation), October 2009

The International Space Station (ISS) is an engineering marvel that is a testimony to human ingenuity and a sterling example of international cooperation for the purpose of conducting unique research in space. As the only existing and available platform of its kind, it is essential that its presence and dedication to research for the life and physical sciences be fully utilized in the decade ahead. Before the 2010 budget announcement, NASA's research plan for ISS utilization was expected to focus on objectives required for lunar and Mars missions in support of Constellation timelines, and ISS participation by the United States was expected to end in 2016. There is now a de-emphasis on lunar missions along with the extension of the ISS mission to 2020. The change in focus strengthens rather than weakens the need for a permanent research laboratory in microgravity devoted to scientific research in space focused on both fundamental questions and questions posed in response to the envisioned needs of future space missions.

In accordance with the charge (see the appendix) for this interim report, this chapter identifies some of the broad research areas that represent near-term opportunities for ISS research. However, it should be understood that flight research is generally part of a continuum of research that extends from laboratories and analog environments on the ground, through other low-gravity platforms as needed and available, and eventually into extended-duration flight. Like any process of scientific discovery this process is iterative, and further cycles of integrated ground-based and flight research are likely to be warranted as understanding of the system under study evolves. Separating out a portion of the research continuum that would benefit from relatively near-term access to the ISS was therefore a significant challenge for the committee, which asks that readers keep the following in mind.

- While the ISS is a key and unique component of research infrastructure that will need to be utilized by a life and physical sciences program, it is only one component of a robust program. Other platforms and elements of research infrastructure will be important, including those that are ground based.
- Because of the limited amount of research time that will be available on the ISS even with an extended lifetime, most of the research that will be flown on the ISS will need to be supported by a very strong ground-based program to be scientifically credible.
- The research discussed here includes both enabling research (associated with the development of new knowledge that could be applied to exploration mission needs) and enabled research (associated with the development of new knowledge that can be obtained only by using the unique microgravity environment of space).

The research discussed below is divided into general fields of life and physical sciences that are amenable to study on the ISS. These fields are not presented in any priority order.

PLANT AND MICROBIAL RESEARCH

Plant and microbial research on the ISS fulfills two major goals: (1) to increase basic knowledge of how these organisms sense and respond to their environment, especially gravity-related phenomena, and (2) to provide the underpinning for enabling sustained human habitation in space.

There has not been a comprehensive program dedicated to analyzing microbial populations and responses to spaceflight. This represents a critical gap in our knowledge because microbial populations play significant roles in positive and negative aspects of human health and in the degradation of their environment through, for example, food spoilage and biofouling of equipment. At present there is little information on how long-term contact with the combination of factors imposed during spaceflight, such as chronic exposure to cosmic radiation and altered physical parameters associated with microgravity such as reduced convection, could lead to changes in microbial populations or provide sufficient selective pressures to drive microbial evolutionary processes. Also, the degree to which such changes reflect physiological responses to the spaceflight environment versus genomic changes remains undefined. Continued access to the ISS coupled to the technological maturity, low cost, and speed of genomic analyses, plus the rapid generation time of microbes, makes monitoring of the evolution of microbial genomic changes induced by extended growth in space a highly feasible short-term goal. Since samples could be taken from the surfaces of the ISS and the crew on board and returned for analysis on the ground, the on-orbit portion of this research could largely be accomplished using the already-existing microbial air and surface sampler kits. This research would allow a comprehensive analysis of microbial population changes in response to the factors present in the spaceflight environment that impact the rates of reproduction or survival of microbes, using both experimentally established populations and samples of microbes colonizing the surfaces and the crew of the ISS.

In contrast, a series of experiments on the ISS with a focus on plants has provided an initial, limited characterization of plant responses ranging from the developmental and molecular changes elicited by spaceflight to changes in photosynthesis, phototropism, and gravisensing in this environment.[1,2]

One aim of this research has been to acquire basic knowledge to enable the use of plants for long-term life support in extraterrestrial habitats by capitalizing on plants' ability to provide fresh food and to aid in the recycling of air, water, and waste products. Establishing the robust elements of such a bioregenerative life support system, which will likely incorporate a combination of biological systems and physico-chemical technologies, requires extended research now that carefully integrates ground- and ISS-based work. Levels and quality of light, atmospheric composition, nutrient levels, and availability of water are all critical elements shaping plant growth in space, where each needs to be optimized in a rigorously tested technology platform designed to maximize plant performance during spaceflight. Although such a research program will be enabled by access to the unique environment of the ISS, it is fundamentally aimed at enabling the long-term human presence in space. Developing a sustained research program combining ground- and ISS-based design and validation of components will be critical to establishing the dynamic integrated intramural and extramural research community necessary to support this area. Food plants will be a cornerstone of this effort because they alone can synthesize nutritious, edible biomass from carbon dioxide (CO_2), inorganic nutrients, and water while revitalizing the atmosphere using the energy of light. However, microbial reactors will likewise require attention to ensure that they can reliably and efficiently process the solid, liquid, and gaseous wastes of habitation. The ISS provides a key enabling resource for beginning to test the efficacy of each component of a long-

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[1] C. Wolverton and J.Z. Kiss, An update on plant space biology, *Gravitational and Space Biology* 22(2):13-20, 2009.

[2] C.A. Evans, J.A. Robinson, J. Tate-Brown, T. Thumm, J. Crespo-Riche, D. Baumann, and J. Rhatigan, *International Space Station Science Research Accomplishments during the Assembly Years: An Analysis of Results from 2000-2008,* NASA/TP-2009-213146–Revision A, NASA, Washington, D.C., 2009.

term life support system in the spaceflight environment, with the long-term goal of facilitating translation from basic research to reliable, applied systems.

Inextricably linked to such a program oriented toward the development of bioregenerative life support technology is the need for research into the fundamental mechanisms behind plant and microbial responses to spaceflight. Despite identification of a range of molecular components linked to gravity perception in plants, currently still unknown are the precise molecular identities of the receptors that translate the physical force of gravity to cellular signal(s) and the immediate signals generated by this sensory system and the associated response components. Similarly, understanding how the often extreme environments of spaceflight—ranging from high ethylene levels in the local air to lack of surface gas exchange due to the absence of convection in microgravity—affect microbial and plant growth is a key gap in current knowledge. Research addressing these questions will contribute to advances in basic understanding of how plants and microbes perceive and respond to the many stimuli present in space. In addition, it will provide essential insight into how these organisms might be selected or engineered, or how their growth environment might be manipulated so as to better tailor them to support a safe, sustained human presence in space. Such a research program studying the sensing and responses of plants and microbes to individual components of the spaceflight environment such as altered gravity, radiation, and atmospheric composition, and to the integrated effects of these multiple factors, will need to combine a robust ground-based program with ISS-based experimentation.

Existing ISS facilities, such as the European Modular Cultivation System, should allow rapid implementation of initial elements of microbial and plant research programs. Extended access to the ISS is essential for the success of these programs because it is currently the sole facility available to test plant and microbial responses in the complex, unique environments presented by spaceflight and especially to test these responses against the background of microgravity.

It is also important to note that new analytical approaches developed over the past decade have redefined understanding of biology in terrestrial settings at the molecular, developmental, and cellular levels. The study of spaceflight biology is poised to take advantage of this new knowledge and the techniques such as genomics, transcriptomics, proteomics, and metabolomics that have enabled it. It is clear that the recent massive strides in genome sequencing, for example, could revolutionize the design of experiments that can be conducted in space by allowing scientists to answer fundamental questions about the role of gravity in transcriptional regulation in biological systems. In the near term, these analyses can be accomplished by sample return and analysis on the ground. However in order to maximize scientific return via on-orbit analyses, and so minimize the currently major limitation of sample return needed for subsequent analysis, a technology development program could be initiated to take advantage of these recently developed, systems-level analytical technologies for investigations associated with the ISS. Such on-orbit analyses would enable research with a wide range of biological specimens, greatly facilitating, for example, the continuous monitoring of microbial genomes described above. The requisite technology development program will need to be initiated in the near-term if such tools are to become available while the ISS is in operation. It will also need to apply modern cell and molecular approaches and integrate a vigorous spaceflight and ground-based research program aimed at assessing the feasibility of implementation and the subsequent development of automated technology to allow these kinds of state-of-the-art molecular analyses on orbit. The resulting extensive data sets will provide the basis for analysis by large numbers of researchers and interdisciplinary teams, thus adding significant value to the limited and costly access to the ISS.

BEHAVIOR AND MENTAL HEALTH RESEARCH

The Augustine Committee Final Report[3] pointed to the fact that future astronauts will face three unique stressors: (1) prolonged exposure to solar and galactic radiation; (2) prolonged periods of exposure to microgravity; and (3) confinement in close, relatively austere quarters along with a small number of other crewmembers with whom the astronaut will have to live and work effectively for many months, with limited contact with family and friends. All of these stressors are present in the ISS environment, although the level of radiation is likely to be lower there than on a space mission because the ISS flies under the Van Allen belts, which provide some protection against charged particle radiation. Accordingly, ISS research studies could profitably determine mission-specific effects of these and other relevant stressors, alone and in combination, on astronauts' general psychological and physical well-being and their ability to perform mission-related tasks. In addition, the ISS platform provides an ideal laboratory for developing techniques to predict and/or monitor the psychological and behavioral status of astronauts, and to develop and test interventions to prevent and/or treat adverse behavioral responses during extended space missions.

There are three key program areas for behavioral mental health research on the ISS:

1. *Individual and group functioning.* Studies are needed to assess how psychological well-being impacts astronaut effectiveness and accomplishment of mission goals. Similar issues pertain to team cohesiveness and effectiveness, increased crewmember autonomy, and crew-groundcrew interactions. For instance, there is accumulating evidence that longer-duration missions are associated with unusual psychological morbidity (symptoms of fatigue and exhaustion, weakness, and emotional lability and irritability, as well as difficulties in concentrating). Careful characterization of such symptoms as well as development of effective interventions is crucial for longer-term missions. Clearly, this is a research area that can best be addressed with continued study on the ISS.
2. *Cognitive functioning.* Because space is a hostile and unforgiving environment, even small errors in judgment or coordination can produce potentially catastrophic effects. To the extent possible, it is important that the cognitive capacity of astronauts be monitored using "embedded" measures—e.g., reaction time when working at a computer monitor or efficiency in operating a robotic arm—typical mission-related duties from which data could be culled to determine the individual astronaut's cognitive status, thereby reducing the need for more extensive cognitive testing. Future cognitive tests would need to be validated against specific, mission-relevant tasks.
3. *Sleep.* NASA has a long history of recognizing the importance of sleep and circadian rhythms in crew health and performance. This emphasis on sleep has been appropriate, since it is clear that adequate sleep is necessary for normal cognitive functioning and that individuals are poor at recognizing the extent of their decreased cognitive performance in the face of sleep loss. Studies are needed to measure the extent to which sleep plays a role in maintaining mental, physical, and cognitive resilience during space missions—and the extent to which sleep-enhancing interventions reverse stress-related symptoms and restore and sustain mental resilience.

The ISS offers a unique platform for this type of research. Whereas analog environments can advance knowledge in these areas, they are limited in terms of the duration of exposure, the crowdedness of the living situation, the implacable hostility of the isolated and confined environment, and loneliness juxtaposed with an excess of face-to-face crew interaction. Similarly, analog environments are limited in terms of their ability to provide crews with characteristics comparable to those likely for crews on the ISS. More fundamentally however, such analog environments are limited in terms of their ability to mimic long-term low gravity and constantly fluctuating circadian rhythms. Finally, the ISS also offers a

[3] Review of U.S. Human Spaceflight Plans Committee, *Seeking a Human Spaceflight Program Worthy of a Great Nation,* Final Report, 2009, available at http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf.

platform for facility design and habitability so that issues of crowdedness versus isolation can be optimally addressed.

The facilities needed to advance behavioral and mental health research on the ISS are relatively modest. The most crucial "facility" needed on the ISS to advance this field is the *will* and *commitment* to exploration of the effects of extended space missions on all aspects of human functioning. As summarized elsewhere in this report, there are substantial problems with translational research efforts in space. The major reason for having an ISS is to provide a research platform. One of the key pieces of "apparatus" on this platform is its human "cargo"; yet, there have been long-standing problems with obtaining research cooperation from astronauts as well as accessing data from prior missions. In terms of other facilities needed, the equipment needs for this research area are generally modest in terms of size or mass. Sleep-monitoring equipment, for instance, has become dramatically smaller in terms of its "footprint." Most of the other behavior and mental health research topics are facilitated by virtue of a strong communications link between the ISS and Earth—a link that can be used for communicating important diagnostic information as well as providing therapeutic links with Earth.

HUMAN AND ANIMAL BIOLOGY

The National Aeronautics and Space Administration Act of 2005, e.g., Article 3 of Section 305,[4] directs the United States to have a national laboratory aboard the ISS to conduct animal and human space-directed research; hence the extension of the availability of the ISS to 2020 and beyond provides a platform to fulfill two major goals: (1) to increase both basic and translational knowledge of animals and humans on a variety of systems that are adversely affected by a microgravity environment and (2) to develop potential countermeasures to alleviate these deficiencies in physiological homeostasis.

A large body of previous research on both animals and humans has clearly established that microgravity and equivalent ground-based analogs induce deficits/alterations in cardiovascular homeostasis, bone mass and strength, muscle mass, strength and endurance, sensorimotor function, thermoregulation, and immune function. As a result, many gaps in knowledge have been defined across these systems that need to be explored to maintain the necessary functional homeostasis when humans are faced with altered gravitation on future missions. Although this section identifies some of the key research issues (most of which have been identified previously by NASA and in earlier studies), the large number of affected physiological systems precludes even a brief discussion of every system in this interim report. The committee's final report will contain an extensive discussion of questions in animal and human biology.

The ISS provides the only opportunity to carry out both fundamental and translational research on organ and systemic function in the absence of the gravity variable. Moreover it provides the optimal environment to establish key countermeasures toward maintaining homeostasis across various organ systems and to initiate interventions that cannot be effectively duplicated by studies using ground-based analogs.

The ISS provides the only opportunity to probe fundamental questions about the role of gravity in developmental biology by examining how animals grow, develop, mature, and age over a large portion of their life span without the influences of gravity. The ISS provides the only means to study, without the stimulus of gravity, these fundamental questions by (1) raising multiple generations of living mammals in space and (2) utilizing transgenic animal models (e.g., overexpression and/or knock-down of transcription factors and altered gene function, including the evolving field of epigenetics) to understand gene regulation of fundamental cell processes. Ethically and practically, these types of experiments cannot be conducted on humans. Equally important is the opportunity to obtain key functional physiological measurements in microgravity that have been unobtainable in previous science missions. This unique

[4] National Aeronautics and Space Administration Authorization Act of 2005, Public Law 109-15, 119 Stat. 2895, December 30, 2005.

knowledge can be gained only via the inclusion of animal studies on the ISS. To carry out these novel animal experiments, an animal facility capable of housing rodents[5] is necessary to conduct current and future generational experiments that are essential to accomplishing these goals. Equipment-sharing agreements with international partners will be necessary for the successful completion of any centrifugation studies using rodents. In summary, the establishment of a rodent habitat on the ISS is a critical need.

As noted above, exposure to microgravity leads to homeostatic deficits across the key systems necessary for the maintenance of health, fitness, and performance. To date, however, none of the exercise countermeasure strategies have been successful in maintaining cardiovascular fitness, muscle mass, strength or endurance, and sensorimotor function, as well as bone mass and strength. For example, recent findings for ISS astronauts who have been in space for 6 months or longer and performing the recommended exercise countermeasures indicated that the countermeasures were unable to prevent the loss of muscle mass or the decrement in muscle performance.[6] Normal function of these systems is necessary for maintaining crew performance capability on return to Earth or entry into other gravitational environments. The ISS is the critical laboratory for conducting studies on countermeasures because this platform creates the capability for supporting long-term exposure in microgravity while testing whether a given countermeasure has the capability for maintaining normal function for long durations in microgravity. Success in maintaining approximately normal homeostasis on the ISS would benefit astronauts traveling to all currently proposed destinations (the Moon, asteroids, Mars, Lagrange points) with their different gravities. Hence, both basic and applied research is needed to integrate information on (1) the responsible mechanisms impacting structural and functional deficits and (2) the translational effectiveness of countermeasures for correcting them. For example, it is envisioned that integrated research teams will be assembled to simultaneously study the interactions between the skeletal muscle, bone, and sensorimotor systems and/or linkage between cardiovascular, sensorimotor, and skeletal muscle systems, as examples of crosscutting thematic research projects. Other studies could integrate pharmacological and mechanical stress investigating maintenance of bone homeostasis. The key is that multiple systems and paradigms would be investigated. Hence, a program is needed to test the effectiveness of (1) a variety of devices and (2) potential integrated exercise regimens, especially those that can impact multiple systems. It appears that mechanical loads during countermeasures have not been appropriate to provide 1-*g*-like loading. Studies to test appropriate countermeasures are urgently needed. Emerging pharmacological interventions to prevent bone and muscle loss also need to be explored.

These kinds of integrative studies can also lead to insights in several divergent areas that have not been explored extensively in the microgravity environment of the ISS. These include but are not limited to bone formation versus resorption processes; fracture repair; reduction of the risk factors for renal stones; net protein balance and contractile protein turnover in skeletal muscle; substrate and organism energy turnover capacity during exercise; the prevalence of cardiac atrophy; head-ward fluid shifts and visual acuity; the mismatch in functional integration of sensorimotor circuits; the verification of the hypothesis that vestibular dysfunction is the cause of motion sickness; the alteration of Starling forces in the microgravity environment; the deposition of different sized aerosols in lung tissue; altered thermoregulation during extravehicular activity (EVA); alterations in female reproductive function and human spermatogenesis; and T-cell activation in astronauts prior to and following re-entry as a result of spaceflight.

In summary, a strong rationale exists for evolving new directions in NASA's approach to human and animal research. Studies on human countermeasures with new approaches to loading and pharmacological interventions in the context of thematic studies need to be considered, and animal studies can provide new insights concerning the mechanism of organ system alterations. Thus, the ISS has great

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[5] Rats and mice are the key model systems used by scientists to understand how gravity affects physiological processes in humans.

[6] S. Trappe, D. Costill, C. Gallagher, A. Creer, et al., Exercise in space: Human skeletal muscle after 6 months aboard the International Space Station, *Journal of Applied Physiology* 106:1159-1168, 2009.

potential to provide new knowledge of the effects of gravity and of its absence on human and animal systems and to test countermeasures for these effects.

FUNDAMENTAL PHYSICAL SCIENCE

The goals of the fundamental physical sciences are (1) to explore the laws governing matter, space, and time and (2) to discover and understand the organizing principles of complex systems from which structure and dynamics emerge. To achieve these goals, fundamental physical sciences researchers have a well-established need for access to space. Specifically, use of the ISS for this research can support achieving groundbreaking results, and in fact the fundamental physical sciences community has had significant experience with space-based research that has produced some high-impact results aboard the ISS. This community has included some of the best scientists of our time—several Nobel laureates as well as principal investigators who have become leading national science policy makers. At present the highest-priority areas for a pioneering, next-generation ISS program are (1) soft condensed matter physics and complex fluids, (2) precision measurement of fundamental forces and symmetries, (3) quantum gases, and (4) condensed matter and critical phenomena. Fundamental physical science research in space is unique in that it is almost entirely "enabled by" exploration, although in the long term this work may enable NASA's exploration mission through the development of new materials and energy sources, time and frequency standards for navigation, and technologies that help humans adapt to the hostile conditions in space.

Soft Condensed Matter and Complex Fluids

Soft condensed matter and complex fluids are materials with multiple levels of structure. Key systems for study include colloids, polymer and colloidal gels, foams, emulsions, soap solutions, and so on because of the gradients that are formed in their properties under gravity. The ISS provides a unique opportunity to remove these gradients and study long-time dynamics free from gravitational interference. Very similar issues exist for complex and dusty plasmas, where density and morphology are height dependent under gravity. Similarly, in granular materials, stress chains and yield properties are height dependent and sensitive to the magnitude of gravity. NASA realized the importance of microgravity research to this field from its infancy, and some of the most significant discoveries were reported at NASA meetings, including highly cited papers coauthored with astronauts. Looking ahead, one example of highly relevant research is the experimentally tested, constitutive equations that describe the strain-strain rate relationships for granular materials under reduced gravity. (It is noteworthy that the Mars Rover "Spirit" has been stuck in the martian soil, a granular material, since May.) In terms of broader impact, along with the fundamental importance of complex fluids/soft materials, their manipulation is a ubiquitous part of the food, chemical, petroleum, cosmetics, pharmaceutical, and plastics industries.

Precision Measurements of Fundamental Forces and Symmetries.

The ISS offers unique conditions to address important questions about the fundamental laws of nature. In particular, the ISS can support high-precision measurements that probe understanding of gravity as well as theories of high-energy physics in ways that are not practical on Earth. Consider some examples: (1) Atomic-physics-based tests of the equivalence principle can probe whether different kinds of matter interact with gravity in the same way. If a violation of this principle is observed, it could offer understanding of dark energy and evidence for quantization of gravity, some of the most important ideas of our time. (2) Since the time of Einstein, physicists have been seeking an "ultimate theory" that ties together gravity, particle physics, and quantum physics. Recently it has been realized that such a theory might involve violations of very fundamental symmetries (e.g., Lorentz symmetry—the idea that the fundamental laws of nature are the same in any inertial reference frame). ISS-based experiments could provide a several-orders-of-magnitude improvement in our search for such violations. A typical experiment might consist of clock comparisons, in which two or more high-stability, ISS-based clocks are simultaneously operated and their timing compared and correlated with position and velocity in gravity.

Quantum Gases

When the temperature of a gas is decreased the quantum, wavelike properties of the constituent atoms or molecules can dominate the behavior of the gas, and remarkable cooperative behavior can emerge. For many gases this can represent the formation of a novel state of matter known as a Bose-Einstein condensate (BEC). A closely related state of a solid is the superconductor, and for a fluid it is the superfluid. In 2001, then NASA-supported fundamental physical scientist Wolfgang Ketterle shared the Nobel Prize in physics for realizing a BEC in his laboratory. The key to creating a BEC is to cool the gas to within nanokelvin temperatures above absolute zero. The lowest achievable temperature is currently limited by the effects of gravity; however, on board the ISS BEC temperatures on the order of a picokelvin (0.000000000001 degrees above absolute zero) should be achievable. A remarkable range of different physical phenomena can then be investigated. If the particles of the quantum gas are "fermions" (particles are classified as either "bosons" or "fermions"), then another class of physics can be investigated. Cold fermion research could address wide-ranging problems such as the unresolved mechanism of superconductivity in high-temperature superconductors. Overall, experiments with quantum gases on the ISS will allow the study of matter in regimes not achievable on Earth. This research will also support new futuristic devices such as the atom laser—a bright source of coherent matter waves analogous to coherent light waves of the familiar laser. Such devices form a basis for next-generation technologies and quantum sensors. An exciting example is the atom interferometer, which has already been tested as a rotation sensor and which can be used for the measurement of fundamental quantities such as the photon momentum and the local force of gravity. As rotational sensors for inertial navigation, these devices rival the best gyroscopes available and are potentially important for space navigation applications.

Condensed Matter and Critical Phenomena

One of the great scientific successes enabled by the microgravity environment over the past two decades concerns better understanding the nature of materials at a very special transition known as a critical point. At this critical point the distinction between the liquid and vapor phases disappears, creating a fog-like critical state that fluctuates wildly. Many other important materials, including superfluids, magnetic materials, and colloids, undergo similar transitions so that work on one system affects understanding of many different systems of recognized scientific and technological interest. Already, a new series of ISS-based experiments have been conceived and designed that will elucidate fundamentally new effects that can be observed when a system near its critical point is driven away from equilibrium, both in the bulk and near boundaries such as a container wall.

Fundamental Physical Science Facilities and Opportunities

In addition to having a track record of successful spaceflight experiments, the fundamental physical sciences community has already developed a portfolio of projects to a level of advanced flight readiness. With renewed NASA support and continued, successful peer review, these projects provide an opportunity to obtain a well-defined, rapid science return from the ISS national laboratory. In general ISS-based fundamental physical science experiments are not facility oriented, with one exception—the Low-Temperature Microgravity Physics Facility (LTMPF). A facility designed to attach to the ISS, LTMPF is engineered to support experiments on critical phenomena and precision measurement experiments as discussed above. It is approximately 70 percent complete, and once finished, it will enable deployment of the flight-ready experiments aboard the ISS.

APPLIED PHYSICAL SCIENCES AND TRANSLATIONAL RESEARCH

Applied physical sciences research on the ISS will accomplish two major goals: (1) to provide a foundation for the development of systems and technologies enabling human and robotic space exploration and (2) to enhance understanding of phenomena enabled by the reduced-gravity environment on the ISS. NASA's future exploration missions will include long-duration, microgravity and partial gravity conditions as well as extreme thermal and radiation environments. Research on the ISS directed toward the first goal will contribute to the development of power generation and energy storage systems; space propulsion systems; systems for EVA; life support systems; fire prevention, mitigation, and recovery systems; materials production and storage; in situ resource utilization (ISRU); and habitat construction and maintenance. Research on the ISS directed toward the second goal could lead to new and fundamental discoveries that would advance exploration and also have beneficial terrestrial applications.

Applied and Translational Research on the ISS That Will Enable Exploration

Power generation and energy storage systems for NASA's future missions will require power at a level ranging from a few watts (for microsatellites) to tens of kilowatts and perhaps megawatts. For low power requirements, systems based on technologies such as thermionics and thermoelectrics are preferred. For higher power, i.e., kilowatts per kilogram, Sterling, Brayton, and Rankine cycle technologies are more suitable. NASA's power generation, storage, and heat rejection technology requirements in the coming decades will be driven by applications such as near-Earth science platforms, lunar and planetary surface missions, and deep-space exploration probes. Increasing the efficiency and lifetime of power generation and energy storage systems will reduce costs by reducing mass and redundancy. All of these systems will benefit from research, prototyping, and testing on the ISS.

Power generation systems include photovoltaic, solar thermal power, and nuclear power systems. For space power generation applications, concentrating solar-thermal power systems have the highest kilowatts-per-kilogram capability. In low gravity, such systems can be lightweight, self-erecting gossamer structures supplying both primary and secondary power. Research conducted on the ISS on materials and structures can enable higher-efficiency systems. The ISS also provides a platform for research on environmental effects on solar arrays, such as the effects of plasma arcing, radiation damage, and micrometeroid impact. For energy storage, regenerative fuel cells and lithium-ion and other advanced battery technologies face major development issues in the quest to provide safe, reliable, affordable, long-life solutions to NASA's future energy storage needs. Since such systems are integral to major ISS systems, the ISS is an excellent developmental platform.

Key advantages of power systems based on the Rankine cycle are higher power and small component size because two-phase-flow and heat-transfer coefficients are much larger than those for gas in non-two-phase systems. Two-phase technology is intrinsic to power systems based on the Rankine cycle, as well as to the thermal management, storage, and handling of cryogenics and other liquids in life support and thermal control systems. Unfortunately, little is known at present about the behavior of two-phase flows and associated heat transfer in a reduced-gravity environment. To enable the design of systems utilizing two-phase technology, it is critical that microgravity research in this area be given very high priority for experiments on the ISS while being supported by a relevant ground-based program. Experimental studies of multiphase flow and heat transfer on the ISS will provide scaling of phenomena with respect to gravity, data for validation of analytical/numerical simulation models, and development of design tools for heat exchangers based on two-phase flow. Experiments on the ISS on pool boiling; forced flow boiling including phase separation and flow stability in single and multiple channels; closure relations for interfacial and wall heat; mass and momentum transfer; condensation; and capillary-driven flows would provide significant knowledge for validating computer models and designing systems. A deeper understanding of two-phase flows would impact a host of important technologies, from those for cryogenic fluid handling to nuclear and other high-power sources of energy.

The major design goals for any space-bound thermal management system in power generation and electronic cooling are performance, cost, physical size, and reliability. Earth-based system processes involving phase change and/or multiple phase flow have been shown to have the highest heat transfer coefficient. Testing on the ISS of a complete system including boilers, phase separators, condensers, and radiators would allow meaningful correlations and validations to be made among the Earth-based and reduced-gravity thermal management systems. Such a system testing under microgravity will allow the study of interactions among components and provide data for validation of system-level simulation tools.

A deeper understanding of capillary flow in, for example, plant nutrient transport can aid in the design of technologies for water-processing systems and fluids handling in propellant storage depots. Finally, the Microgravity Science Glovebox and the Fluids Integrated Rack are valuable facilities available on the ISS. It would be useful to consider the utility of developing a multipurpose, multiuser facility on the ISS for multiphase flow research. Such a facility would also act as a catalyst for bringing together national and international researchers to address the challenge in a cost-effective and comprehensive manner. The merits of single-purpose experiment packages would need to be weighed in such an assessment as well.

To support NASA's exploration missions, an evolutionary space transportation architecture is needed for science discovery and technology demonstration. These space propulsion systems will support the large human and cargo missions envisioned as well as pico-spacecraft that capitalize on advances in micro- and nanotechnologies. Advances in propulsion performance (specific impulse, efficiency, thrust to weight, propellant bulk density), reliability, thermal management, power generation and handling, and propellant storage and handling are key drivers to dramatically reduce mass, cost, and mission risk. The ISS provides unique opportunities for research in a number of these areas.

The reduced-gravity environment on the ISS provides opportunities for research on cryogenic two-phase fluid management, propellant transfer, engine starts, flame stability, and active thermal control of injectors and combustors. In addition, the ISS can benefit non-cryogenic (Earth-storable) propulsion systems by providing research opportunities for mixing or separation, and tribology under reduced-gravity. Research conducted on the ISS on physical phenomena involved in heat exchangers, thermal control, Stirling and Brayton cycles, lightweight and high-temperature thermal structures, propellant transfer and management, and liquid metal or noble gas storage under reduced gravity will provide the opportunity for fundamental advances for solar electric, nuclear thermal, and nuclear electric propulsion options. Indeed, the ISS can be an ideal laboratory providing an infrastructure and space environment for the development and demonstration of these non-chemical propulsion options that have a potential to reduce the duration of trips to Mars. In addition, the emerging technology for inflatable and low-mass aerobraking for re-entry systems can benefit from small free-flyer aerothermochemistry experiments conducted from the ISS. Using inflatable structures in re-entry systems to transport laboratory specimens and products from the ISS to Earth can provide opportunities to characterize for prototype return systems such items as vibration and deceleration loads, minimum thermal protection, and costs for a range of cargo types, and to gain operational experience. Currently, the transport of such items is limited to the return capsules or the remaining and available shuttle flights, and so such a system might be useful for more timely return of samples for analyses.

Creation of propellant depots in space that are supplied from propellant sources on Earth (and eventually the Moon) will dramatically improve the architecture and economics of exploration activities beyond low Earth orbit. Supply depots in Earth orbit can utilize a wide range of new-era commercial launch systems. Key science issues that need to be understood to make such depots a reality can be advanced with research on the ISS on cryogenic fluid management, including zero boil-off working fluids, propellant storage, two-phase flows, contact line motion on a solid surface, adhesion forces under low temperatures, and fluid transfer.

For EVA, the ISS environment is ideal for testing and qualifying a wide range of spacesuit mobility and performance innovations, such as joint torque minimization, suit comfort and trauma/injury countermeasures, thermal control, and radiation protection. In addition, EVA innovations in areas such as more efficient power, communication, avionics, and informatics systems can be tested for endurance during extended ISS missions. The ISS is also the ideal platform to investigate plasma interactions with astronauts during EVAs in proximity to space structures that have high-power, high-voltage solar arrays. Research could be performed to address dust and micrometeorite interactions with spacesuits.

Life support systems (LSS)—for pressure control; atmosphere revitalization: removal of carbon dioxide, water vapor, and trace contaminants; temperature and humidity control; and waste collection—are integral to spacecraft habitats, rovers, and EVA. ISS laboratories provide a microgravity environment and facilities to characterize and test such LSS functions as heat and mass transfer in porous media and monitoring to identify major atmosphere constituents and trace contaminants. Innovative approaches can be evaluated to perform closed-loop air revitalization with CO_2 removal, recovery, and reduction; oxygen generation via electrolysis with high-pressure capability; improved sorbents and catalysts for trace contaminant control; and atmosphere particulate control and monitoring. Experiments on the ISS can be conducted to study dust accumulation, particle deposition in lungs, and especially electrostatic effects. Many of these approaches remain undeveloped because of poor understanding of multiphase and capillary flow (for example, for passive solid separation technologies) in reduced-gravity environments.

Fire safety is critical to enabling human exploration of space because fires can have devastating consequences, including loss of life and loss of vehicle or habitat integrity. Historically, fire research has been treated as a subset of combustion research. Basic and applied combustion research using ground-based facilities and in the ISS (Combustion Integrated Rack) have made significant advances that support fire safety research. This research includes characterization of particulates and toxic gases, smoldering, ignition, extinction, and flame spread. Nevertheless, the timely attainment of fire safety substantially depends on an adequate and comprehensive strategy that does not necessarily require a full understanding of the underlying principles of combustion, but is based more on phenomenological models and empirical correlations. As a result, the research and development (R&D) needs for fire safety for human exploration of space relate more to the understanding of how the different components together deliver an adequate fire safety strategy. The critical components are (1) a material's response to fires, (2) fire detection, (3) fire suppression, and (4) recovery from fire (and explosions). The limited facilities, size constraints, and manpower limitations on the ISS restrict progress on the main areas of fire safety research necessary for application to space exploration. Thus, the use of ground-based facilities is particularly critical for a comprehensive fire safety program and will be detailed in the committee's final report.

The link between ISRU on the Moon, Mars, and small bodies (asteroids or planetary moons) and the ISS is indirect. Research aimed at better understanding multiphase fluid flow on the ISS will be helpful for the design of systems for handling fluids in reduced-gravity environments. Also, research aimed at developing a capability for transferring propellant in space could play a part in a future lunar or Mars ISRU-based propellant production and utilization scenario. Research in the ISS relevant to excavation and material transport would also help in situ resource utilization in reduced-gravity environments.

Research activities that could be conducted on the ISS that will be beneficial, even critical, for any future planetary surface exploration involve materials and structural dynamics (self-deploying, inflatable, composite materials), as well as radiation protection systems. Testing on the ISS would benefit continuing development of food preparation, delivery, and storage systems, health maintenance equipment, radiation protection systems and materials, robotic systems, and human-machine interface systems.

Applied Research That Is Enabled by the ISS

Research enabled by the unique microgravity environment and facilities on the ISS can also address unexplored phenomena that have beneficial implications for exploration systems as well as many terrestrial technologies.

Gravity can mask the effects of many important fluid flow phenomena. Areas that can provide new and important insights via experiments on the ISS include flows driven by gradients of surface tension caused by temperature and concentration, solid-liquid adhesion forces, interfacial forces involving shear and pressure forces, electric fields, magnetic fields, acoustic fields, and acceleration. Other examples are spreading, stability, and rupture of ultrathin liquid films. Much can be learned by considering granular materials at reduced-gravity. Key aspects concern effects such as particle clustering, self-assembly, and dissipation; the study of electrostatic effects and interstitial fluids; and the impact of having multiple particle sizes and/or shapes.

In the area of materials synthesis and processing, a microgravity environment can shed new light on the nucleation process because liquids can be suspended and solidified without a container, thus removing the effects of walls, as well as convection due to compositional inhomogeneities that accompany the formation of nuclei. Thus it is possible to study the formation of stable and metastable phases from undercooled melts, the formation of glasses, the relationship between liquid structure and the resulting crystal structure, and the thermophysical properties of deeply undercooled liquids. Understanding the processes leading to the production of materials composed of phases with much different densities, such as metallic and ceramic foams, can be improved by research on the ISS.

On Earth, during crystal growth the density differences between crystals and the parent fluid or vapor—as well as the temperature and composition dependence of the density of the parent phase and variations in the surface tension of a liquid-vapor—lead to convection. This convection results in nonuniform compositions as well as defects in the resulting crystal. The microgravity environment allows these crystal growth phenomena to be studied without the confounding effects of gravitationally induced convection. The Materials Science Research Rack (MSRR) available on the ISS is a very valuable asset.

Gravitationally induced convection or sedimentation makes it very difficult to study the physics that underlie processes such as dendritic and cellular solidification, liquid phase sintering, and phase separation. The effects of interactions between individual dendrites or cells on their spatial distribution and morphology, the evolution of dendrite morphology during transient heating or cooling, and the effects of noise and initial conditions on the resulting patterns remain unclear. The interactions between dendrites are particularly important in setting the properties of a solid-liquid mixture found in castings, called the mushy zone. Fluid flow within mushy zones can become unstable during solidification, resulting in deleterious casting defects. The nature of this instability and the properties of the mushy zone need further investigation.

Studies of combustion in a reduced-gravity environment would lead to a greater understanding of terrestrial combustion. On Earth, energy release, fluid dynamics, and gravity-induced buoyancy interact in a nonlinear fashion. By varying or eliminating the effects of gravity, researchers can extract fundamental data that are important for understanding combustion systems. Such data include parameters such as chemical reaction rates, diffusion coefficients, and radiation coefficients that strongly influence ignition, propagation, and extinction of combustion waves.

It is very rare, on Earth and in space, for an area, cabin, or room to be uniformly filled with a stoichiometric, homogeneous mix of fuel and oxidizer. Unfortunately, very little is known about the behavior of flames propagating through reactivity gradients. Reactivity gradients are important for all stages of a fire or explosion from ignition and propagation through to extinction. Reduced-gravity environments can be used to learn more about flame ignition, propagation, and extinction in reactivity gradients.

It is now speculated that gaseous flammability limits might not exist at all, or that a diffusive or hydrodynamic mechanism may cause extinction, or that flame balls or flame strings are themselves the limiting structure. Most combustors and unwanted fires involve diffusion flames. There remain significant gaps in the understanding of these flames, such as those associated with chemical kinetics, transport, radiation, soot formation, pollutant emissions, flame stability, and extinction. All of these areas will benefit from experiments performed on the ISS.

Appendix:
Statement of Task

BACKGROUND

Consistent with U.S. Space Exploration policy, NASA intends to conduct a series of robotic and crewed exploration missions over the next decades. These include missions to the International Space Station (ISS) and other missions to low Earth orbit and missions to the Moon. These missions will involve a combination of factors such as reduced gravity level, radiation, life support and extended-duration confinement. In addition, these missions present multidisciplinary scientific and engineering challenges and opportunities that are both fundamental and applied in nature. Meeting these scientific challenges will require an understanding of biological and physical sciences and their intersections in partial and microgravity environments.

Previous congressional language in the NASA Authorization Act of 2005 had reserved a portion of space station research funding for fundamental research in life and microgravity sciences. More recently, Congress provided additional direction regarding life and microgravity research (Explanatory Statement accompanying the FY 2008 Omnibus Appropriations Act (P.L. 110-161)) by stating: "Achieving the goals of the Exploration Initiative will require a greater understanding of life and physical sciences phenomena in microgravity as well as in the partial gravity environments of the Moon and Mars. Therefore, the Administrator is directed to enter into an arrangement with the National Research Council to conduct a "decadal survey" of life and physical sciences research in microgravity and partial gravity to establish priorities for research for the 2010-2020 decade."

In early 2010, guidance was provided to NASA in the fiscal year (FY) 2011 Presidential Budget request which would extend the lifetime of ISS to 2020—considerably altering both the research capacity and role of ISS in any proposed program of life and microgravity research. Additional changes initiated by the budget request would greatly affect both the organization and likely scale of these programs at NASA. In order to ensure that the committee could both provide timely input to these organizational changes, and incorporate consideration of their possible impact into its final report recommendations, the committee will develop an interim report focused on key near term issues, followed by a reassessment of its portfolio assumptions and recommendations prior to completion of the final full report.

STATEMENT OF TASK

Consistent with the direction in the Explanatory Statement accompanying the FY 2008 Omnibus Appropriations Act (P.L. 110-161), the National Research Council will organize a decadal survey to establish priorities and provide recommendations for life and physical sciences research in microgravity and partial gravity for the 2010-2020 decade. The committee will develop criteria for the prioritization.

The decadal survey will define research areas, recommend a research portfolio and a timeline for conducting that research, identify facility and platform requirements as appropriate, provide rationales for suggested program elements, define dependencies between research objectives, identify terrestrial benefits, and specify whether the research product directly enables exploration or produces fundamental new knowledge. These areas will be categorized as either those that are required to enable exploration missions or those that are enabled or facilitated because of exploration missions.

The decadal survey should:

- Define research areas that enable exploration missions or that are enabled by exploration missions;
- For each of the two categories above, define and prioritize an integrated life and physical sciences research portfolio and associated objectives;
- Develop a timeline for the next decade for these research objectives and identify dependencies between the objectives;
- Identify terrestrial, airborne, and space-based platforms and facilities that could most effectively achieve the objectives;
- Explain how the objectives could enable exploration activities, produce knowledge, or provide benefits to space and other applications;
- Identify potential research synergies between NASA and other U.S. government agencies, as well as with commercial entities and international partners; and
- Identify potential research objectives beyond 2020.

The results of the decadal survey will assist in defining and aligning life and physical sciences research to meet the needs of exploration missions. The recommendations regarding the timeline and sequence of research are intended to allow NASA to develop an implementation plan that will impact future exploration missions. The survey should focus on the aforementioned tasks and should not recommend budgetary levels. This decadal survey should build upon the findings and recommendations of previous National Academies' studies conducted in this area.

Prior to the publication of the final report, a brief interim report will be developed that is intended to address near term challenges faced by NASA as it reorganizes its programs to comply with directions to NASA in the President's FY 2011 Budget that substantially affect the conduct of ISS science in particular, and life and microgravity science in general. The interim report will focus on issues identified by the committee that relate to:

1. ISS as a platform for conducting life and physical sciences research, and
2. Programmatic support of a healthy and sustainable life and physical sciences research program at NASA.

The interim report will identify programmatic needs and issues to guide near-term decisions that are critical to strengthening the organization and management of life and physical sciences research at NASA. The interim report will also identify a number of broad topics that represent near-term opportunities for ISS research. These areas, along with research more suited to other platforms, will be discussed in greater detail in the final report. In addition to any relevant findings, the interim report may include recommendations to the extent that they are useful and that adequate justification for them can be provided in this short report.